APPENDIX A:

SEISMICITY OF THE DELTA REGION

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A1. INTRODUCTION

The Delta is located in a region of relatively low seismic activity. However, if a large earthquake (M≈6.5-7) occurs on a local fault in the Delta region, then there will be large ground motions (with peak horizontal accelerations exceeding 0.2g) at the western edge of the Delta. Although a large local event cannot be ruled out, it has a low probability of occurring. Probabilistic seismic hazard analysis is a method that explicitly considers how often earthquakes of various sizes are likely to occur, and what is the likely ground motion that will result if an earthquake occurs. In this manner, it allows for an evaluation of the seismic risk of the levees.

The probabilistic approach used in this study follows the standard approach first developed by Cornell (1968), with some modifications to more fully address all sources of variability.

There are three main components of variability that are considered in a seismic hazard analysis: what are the likely magnitudes of the earthquakes, where are the earthquakes likely to be located, and what is the likely ground motion given that an earthquake of a specified magnitude has occurred at a specified location.

The source characterization describes the expected rate of earthquakes as well as the distribution of magnitudes and locations. The attenuation relationships describe how strong the resulting ground shaking will be for an event of a given magnitude and location. These components of the hazard analysis are briefly described below. The resulting horizontal peak acceleration hazard is then discussed.

A2. DESCRIPTION OF SEISMIC SOURCES

The faults considered in the hazard analysis are shown in Figure A-1 and A-2, for the two alternative models of the Delta region thrust faults considered in this study. The mean slip-rate, fault width, and maximum magnitude of the faults are listed in Table A-1. The main strike-slip faults in the Bay area (San Andreas, Hayward, Calaveras) contribute to the hazard in the Delta for short return periods, but the smaller (and more local) faults contribute more significantly to the overall hazard at longer return intervals.

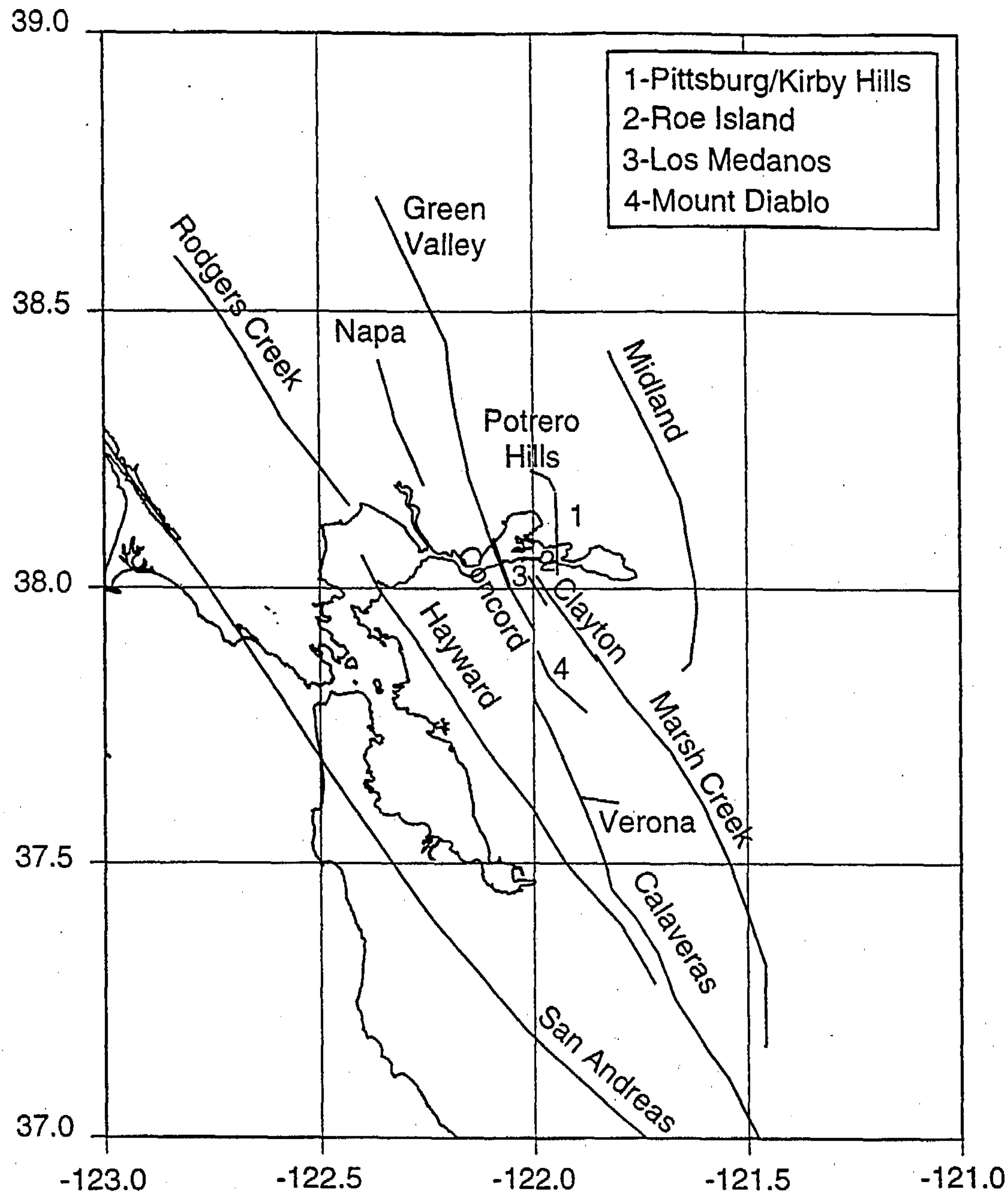

Figure A-1: Map showing the significant faults in the Delta region used in the seismic hazard computations based on the Lettis Delta fault model.

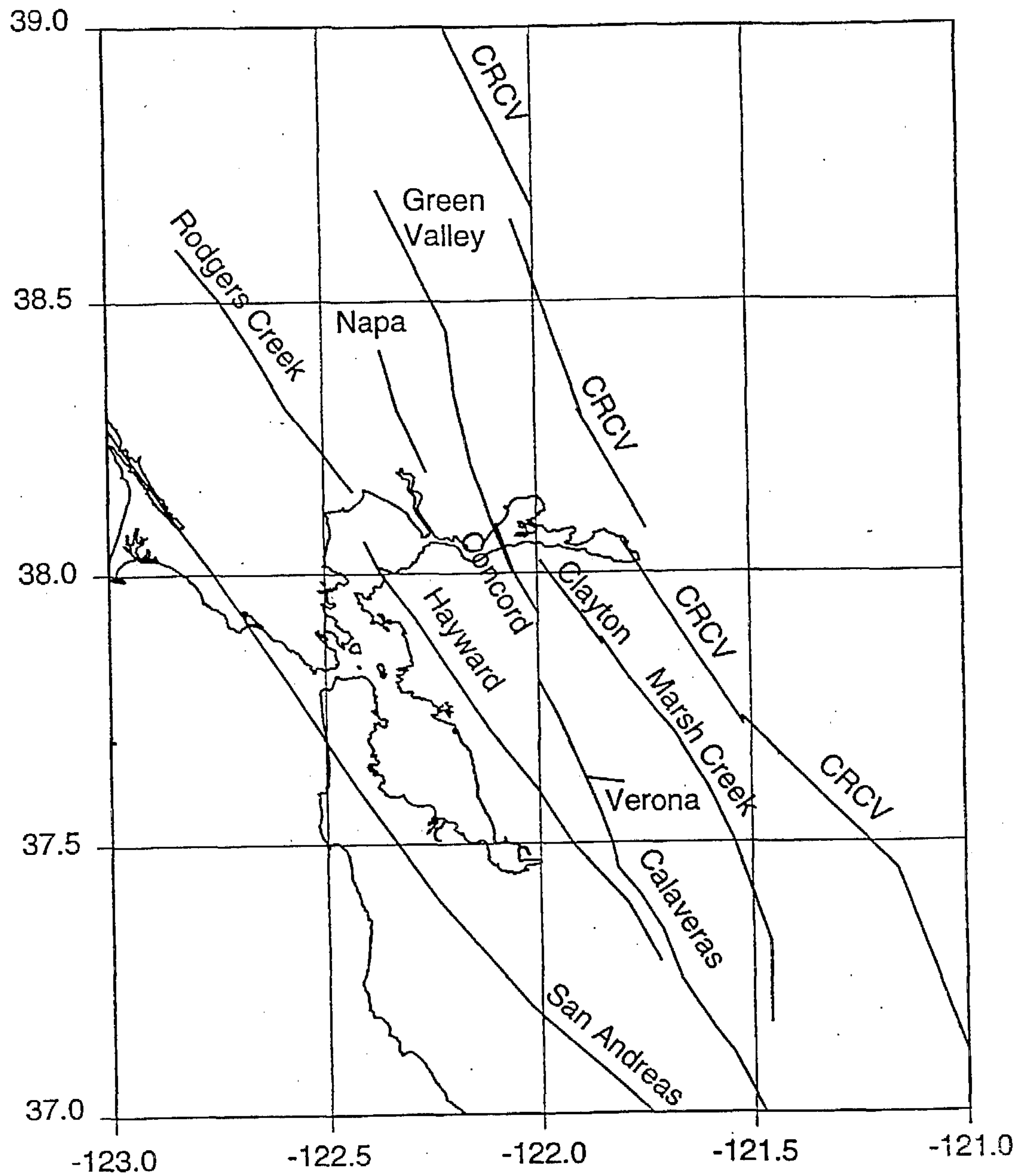

Figure A-2: Map showing the significant faults in the Delta region used in the seismic hazard computations based on the CRCV Delta fault model.

Table A-1. Seismic Source Parameters

Fault	Slip Rate (Weight)	Fault Width (Weights)	Max Magnitude (Weights)
Concord	3.0, 4.0, 6.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.4, 6.6, 6.8 (0.2, 0.6, 0.2)
Calaveras (North)	2.0, 6.0, 8.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.7 (1.0)
Calaveras (South)	13.0, 15.0, 17.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.8 (1.0)
Hayward	7.0, 9.0, 11.0 (0.25, 0.5, 0.25)	12.0 (1.0)	7.1 (1.0)
Marsh Creek/Greenville	0.5, 2.0, 3.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.7 (1.0)
Clayton	0.2, 0.5, 1.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.7 (1.0)
Green Valley	1.5, 4.0, 5.0 (0.2, 0.6, 0.2)	12.0 (1.0)	6.6 (1.0)
Napa	0.1, 0.3, 0.5 (0.3, 0.5, 0.2)	12.0 (1.0)	6.5 (1.0)
Rogers Creek	6.0, 8.0, 11.0 (0.25, 0.5, 0.25)	12.0 (1.0)	7.0 (1.0)
San Andreas	19.0, 24.0, 29.0 (0.2, 0.6, 0.2)	15.0 (1.0)	7.8, 8.0 (0.8, 0.2)
Verona	0.1 (1.0)	10.0 (1.0)	6.1 (1.0)
Antioch	0.3 (1.0)	15.0 (1.0)	6.5 (1.0)
Mt. Diablo Thrust[1]	1.3, 1.7, 5.0 (0.3, 0.6, 0.1)	11.0 (1.0)	6.25, 6.75 (0.30, 0.70)
Los Medanos Thrust[1]	0.3, 0.7 (0.8, 0.2)	13.0 (1.0)	6.00, 6.25 (0.8, 0.2)
Roe Island Thrust[1]	0.1, 0.3, 0.7 (0.1, 0.7, 0.2)	14.0 (1.0)	5.75, 6.00 (0.5, 0.5)
Potrero Hills Thrust[1]	0.1, 0.3, 0.6 (0.3, 0.6, 0.1)	14.25 (1.0)	6.00, 6.25 (0.8, 0.2)
Pittsburg/Kirby Hills Thrust[1]	0.2, 0.3, 0.7 (0.5, 0.4, 0.1)	15.0 (1.0)	6.00, 6.50 (0.4, 0.6)
Midland Thrust[1]	0.1, 0.2 (0.6, 0.4)	13.0 (1.0)	6.00, 6.25 (0.7, 0.3)
CRCV[2]	0.5, 1.5, 2.5 (0.25, 0.5, 0.25)	10.0 (1.0)	6.8 (1.0)

1 Lettis source model for the Delta region.
2 CRCV source model for the Delta region.

In addition to the known faults, a background source zone is also included to capture the earthquakes expected to occur on other fault sources. The background zone is based on the smoothed historical regional background seismicity ($M \geq 4.0$) developed by USGS (1996) and used by the CDMG in its state hazard maps. This background seismicity is smoothed over a distance of 50 km, resulting in very smooth background seismicity. The rate of magnitude 5 or greater earthquakes per 100 years per 100 square km is shown in Figure A-3. To avoid double counting seismicity, the background zone is used for magnitudes 5-6 and the individual known faults are used for magnitudes greater than 6.0.

The two alternative models for the thrust faults are discussed in more detail below.

Delta Region Thrust Faults

Geodetic data indicates that there is crustal shortening of about 3 mm/yr in the direction normal to the San Andreas fault between the Pacific Plate and the North American Plate. The primarily strike-slip earthquakes in the Bay Area region accommodate some of this shortening, but some additional thrust faults are needed to explain the remainder of the shortening between the Pacific and North American plates in this region. These thrust faults generally do not reach the surface and are considered "blind thrust" faults.

In most recent studies, most of the additional shortening has been assumed to be accommodated along the western edge of the central valley along a feature called the Coast Range/Central Valley Thrust (CRCV) fault zone (also called the Coast Range Sierran Block Boundary Zone).

There have been several earthquakes over magnitude 6 that have occurred along the CRCV fault zone to the north and to the south of the Delta region, but there are no known CRCV events of $M \geq 6$ in the vicinity of the Delta. The 1983 Coalinga earthquake ($M=6.4$) and the 1985 Kettleman Hills earthquake ($M=6.1$) occurred on the CRCV. The 1892 Winters-Vaccaville earthquake ($M=6.4$) may also have occurred on the CRCV, but its location is not well constrained (Toppozada, Real, and Parke, 1981). The CRCV is clearly an active fault in some regions, but it may not exist in the Delta region, or it may not be active in the Delta region.

In this evaluation, we consider two alternative models of the thrust faults in the Delta region: the CRCV model and the without CRCV model developed by Lettis and Associates model. These two alternative models are discussed in the following sections.

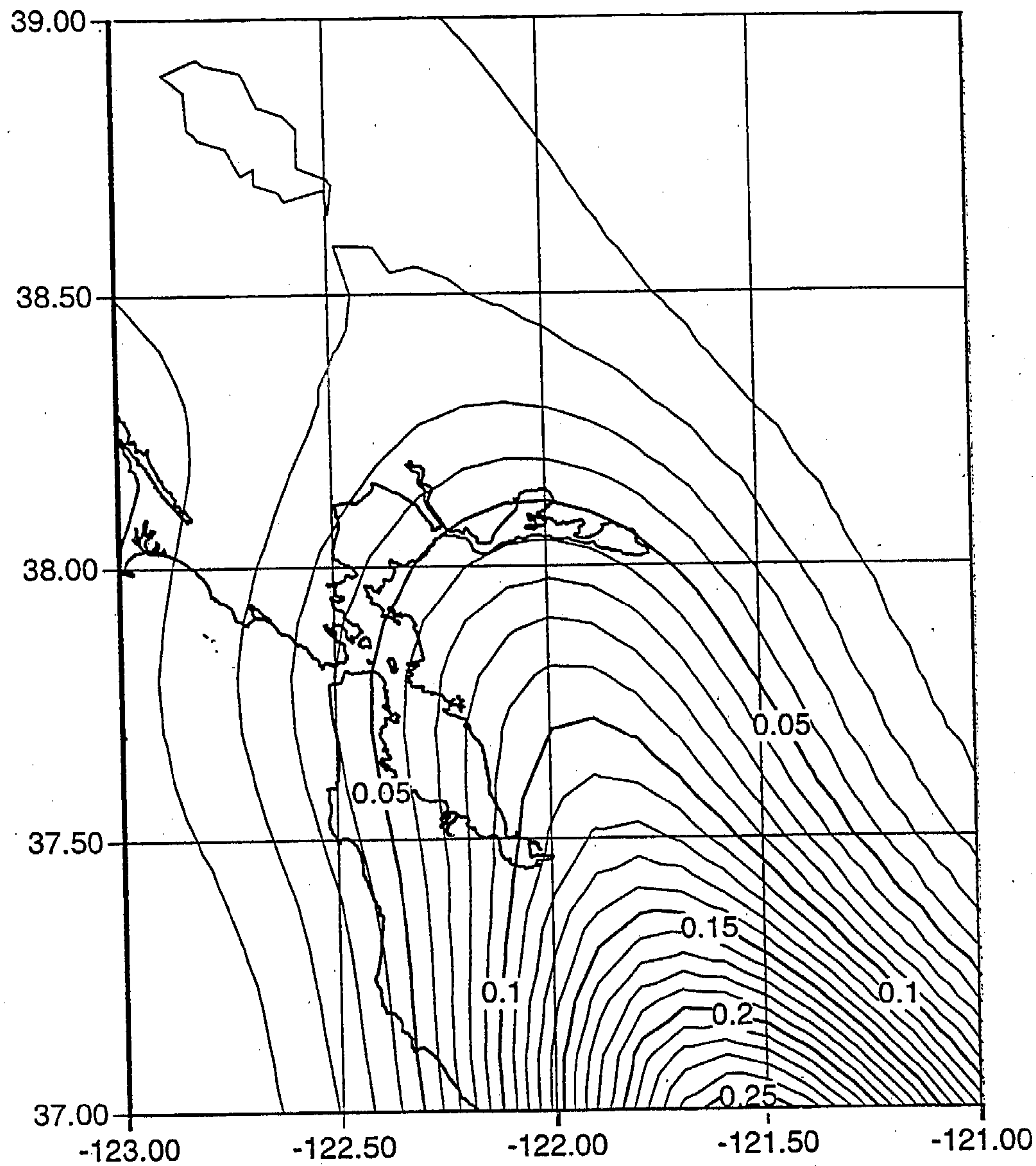

Figure A-3. Map showing the contour of smoothed background seismicity for magnitude 5.0 and greater per 100 years per 100 square kilometers. Based on the USGS gridded seismicity maps (1996).

CRCV Thrust Fault Model

The CRCV extends about 600 km along the western edge of the Central Valley in central and Northern California (Wong et al., 1988), but the faulting is discontinuous. Most of the segment lengths are 5 to 20 km with a maximum segment length of about 50 km. In the CRCV model, this set of thrust faults extends through the Delta region and runs near Sherman Island (see Figure A-2).

The CRCV model has been used in the state hazard maps developed by the California Division of Mines and Geology (CDMG). The slip-rate of the CRCV in the Delta region is uncertain. The sub-team used a range of slip-rates from 0.5 to 2.5 mm/yr. The CDMG (1996) used a slip-rate of 1.5 mm/yr and that is the mean value that is used in this study.

The exact location of the CRCV fault in the Delta region is uncertain. In this study, the top of the fault is located at a depth of 8 km with a dip of 15 degrees. For a down-dip fault width of 15 km and a segment length of 40 km, the Wells and Coppersmith (1994) magnitude vs. fault area relation gives a mean maximum magnitude of $M_w \approx 6.8$.

Without CRCV Model Developed by Lettis and Associates

A recent study by Unruh (Lettis and Associates written comm., 1998) suggests that the CRCV is not present in the Delta region. According to this model, the CRCV begins to decrease in activity north of the San Luis Reservoir and south of Lake Berryessa. In the Delta region, the CRCV ceases to exist, or ceases to be active. As an alternative to the CRCV, the Lettis and Associates model postulates a different set of thrust faults slightly further to the west to accommodate the crustal shortening (see Figure A-1).

These faults, the Pittsburg/Kirby Hills, Roe Island, Los Medanos, and Mount Diablo faults are all short faults with lengths of less than 20 km located 10-20 km west of the western edge of the Delta. The mean slip-rates of these faults range from 0.3 to 2 mm/yr. The maximum magnitudes of the small thrust faults range from $M_w \approx 6.0$ to 6.6.

This model also includes the Midland fault located beneath the Delta, but with a small mean slip-rate of 0.15 mm/yr. Although the Midland fault has a length of about 60 km, the maximum magnitude of the Midland fault in this model is only $M_w \approx 6.2$.

A3. ATTENUATION RELATIONS

There are many attenuation relations that can be used for the deep soil site conditions (below the peat) in the Delta. In this study, we have selected four of the most recent attenuation models: Abrahamson and Silva (1997), Boore, et al. (1997), Campbell

(1997), and Sadigh, et al. (1997) as being appropriate. These models are given equal weight in the hazard analysis.

A4. PROBABILISTIC HAZARD RESULTS

The probabilistic hazard is shown separately for the Lettis and the CRCV models of the Delta thrust faults. The results for the Lettis model are shown first, and the results for the CRCV model are shown second. Sherman Island and Terminous Island are used as example locations representative of the western and eastern edges of the Delta, respectively. All acceleration levels shown are peak horizontal accelerations at surface outcrops of deep, stiff soils (soils underlying the softer and organic superficial Delta deposits.)

Figures A-4 and A-5 show the peak acceleration hazard for Sherman Island and Terminous Island, respectively, based on the Lettis thrust fault model. At a return period of 100 years (annual probability of 0.01), the hazard at Sherman Island is dominated by the local thrust faults, with significant contribution from the background zone and "other" faults. For Terminous Island, the background zone and thrust faults contribute about equally to the overall 100 year return-interval level of hazard.

The magnitudes and distances of the earthquakes dominating the hazard can be estimated by deaggregating the hazard. The distributions of contribution to the hazard are shown in Figures A-6 and A-7. For Sherman Island, the hazard is primarily from moderate magnitude events ($M \approx 5.5$-6.5) at distances of 10 to 30 km. For Terminous Island, the more distant sources also contribute significantly to the hazard, and there is a wide range of magnitudes and distances ($M \approx 5$-6 at distances of 10-30 km to $M \approx 7$-7.5 at 100 km) contributing to the hazard. Figures A-8 and A-9 show the mean magnitude and mean distance of the earthquakes contributing to the hazard as a function of the return period.

A similar set of plots for the CRCV model is shown in Figure A-10 and A-11. The main difference is that for the CRCV model, the local CRCV thrust faults are the principal controlling source for both Sherman Island and Terminous Island.

The hazard for the Lettis and CRCV models is compared in Figure A-12. This figure shows that the hazard from these two models is very similar for both the Sherman Island and Terminous Island sites when expressed in terms of expected peak horizontal acceleration. The models differ, however, in terms of the principal magnitudes that contribute to these acceleration hazard levels. These differences in contributing magnitudes, in turn, imply differences in the duration of shaking, and this has a potentially significant impact on both the liquefaction and cyclic inertial deformation hazard evaluations for Delta levees.

The two models are given equal weight in the final hazard analysis. Contours of the peak acceleration in the Delta region for return period of 43 years, 100 years, 200 years, and 475 years (building code level) are shown in Figures A-13 through A-16. The hazard systematically decreases from the southwest to the northeast.

For the top of stiff soils, the 100 year return-interval horizontal peak acceleration ranges from 0.2 g in the western Delta to 0.1 g in the northeastern Delta. Since the hazard is dominated by moderate magnitude local events, it is unlikely that the entire Delta will be subject to the 100-year ground motion in a single 100-year earthquake.

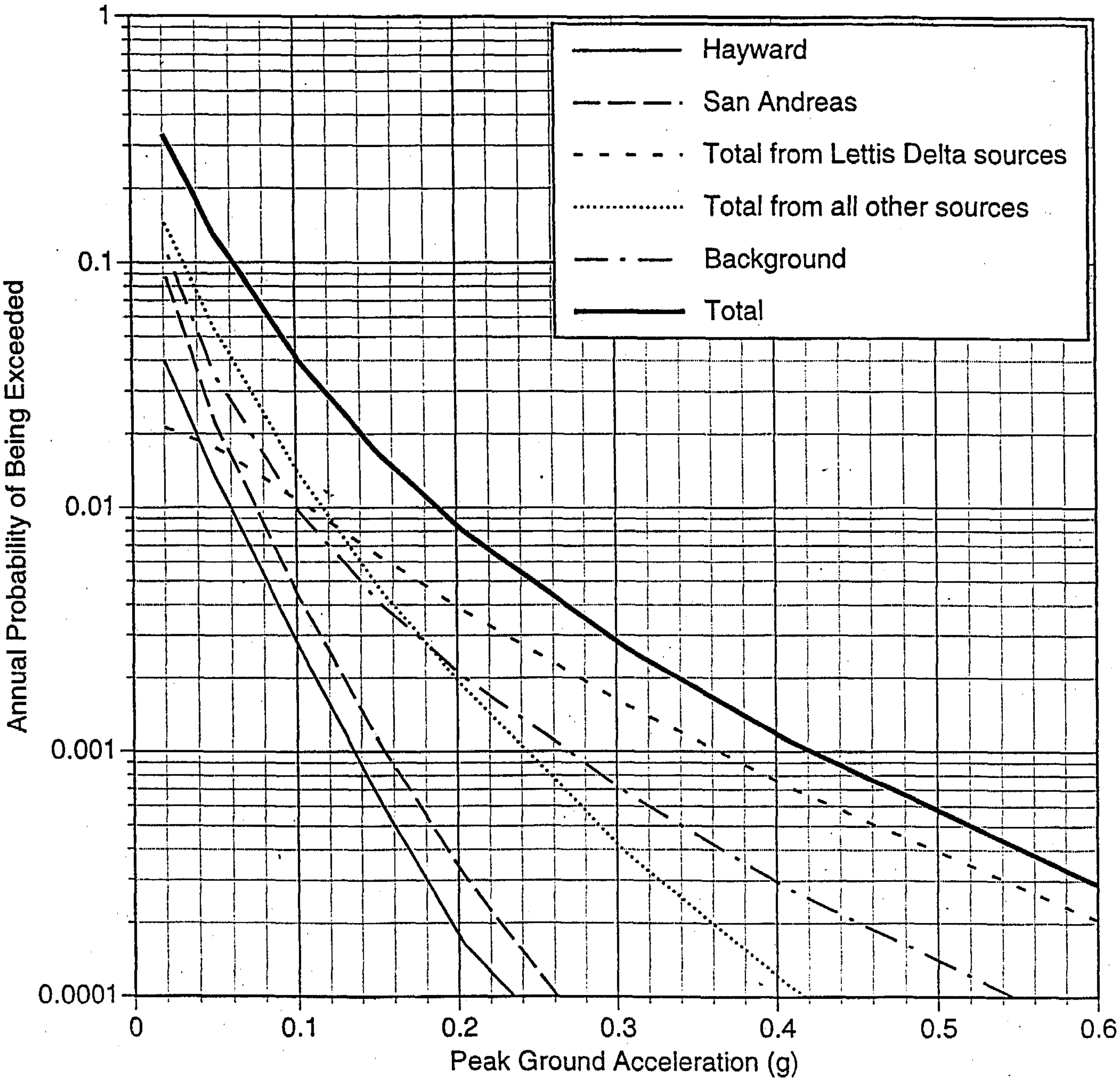

Figure A-4. **Seismic hazard curves for the Sherman Island site. The hazard curves are based on the Lettis seismic model for the Delta region. The contribution to the total hazard is shown for the significant faults.**

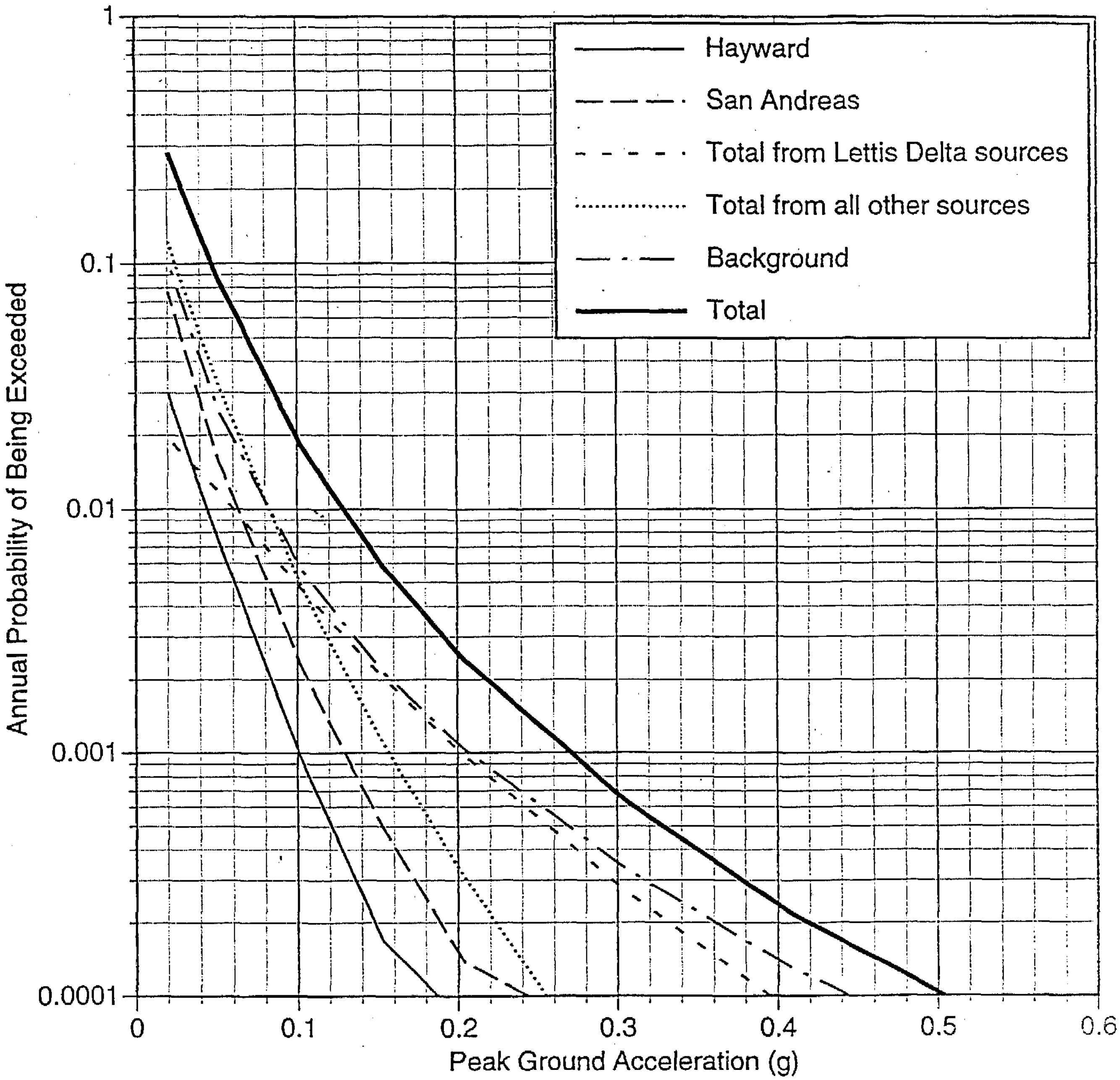

Figure A-5. Seismic hazard curves for the Terminous site. The hazard curves are based on the Lettis seismic source model for the Delta region. The contribution to the total hazard is shown for the significant faults.

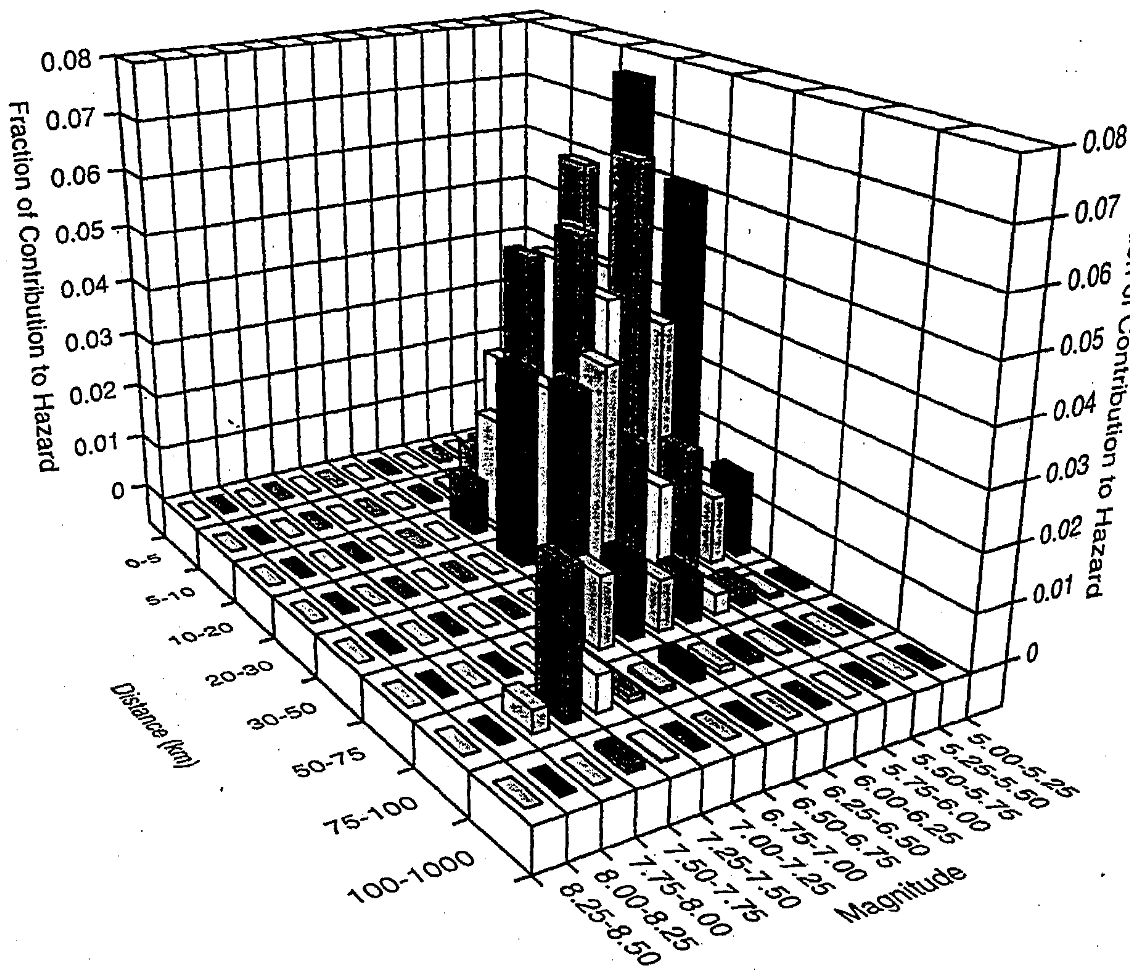

Figure A-6. **Deaggregation of the seismic hazard (100 year return period) for the Sherman Island site based on the Lettis seismic source model for the Delta region.**

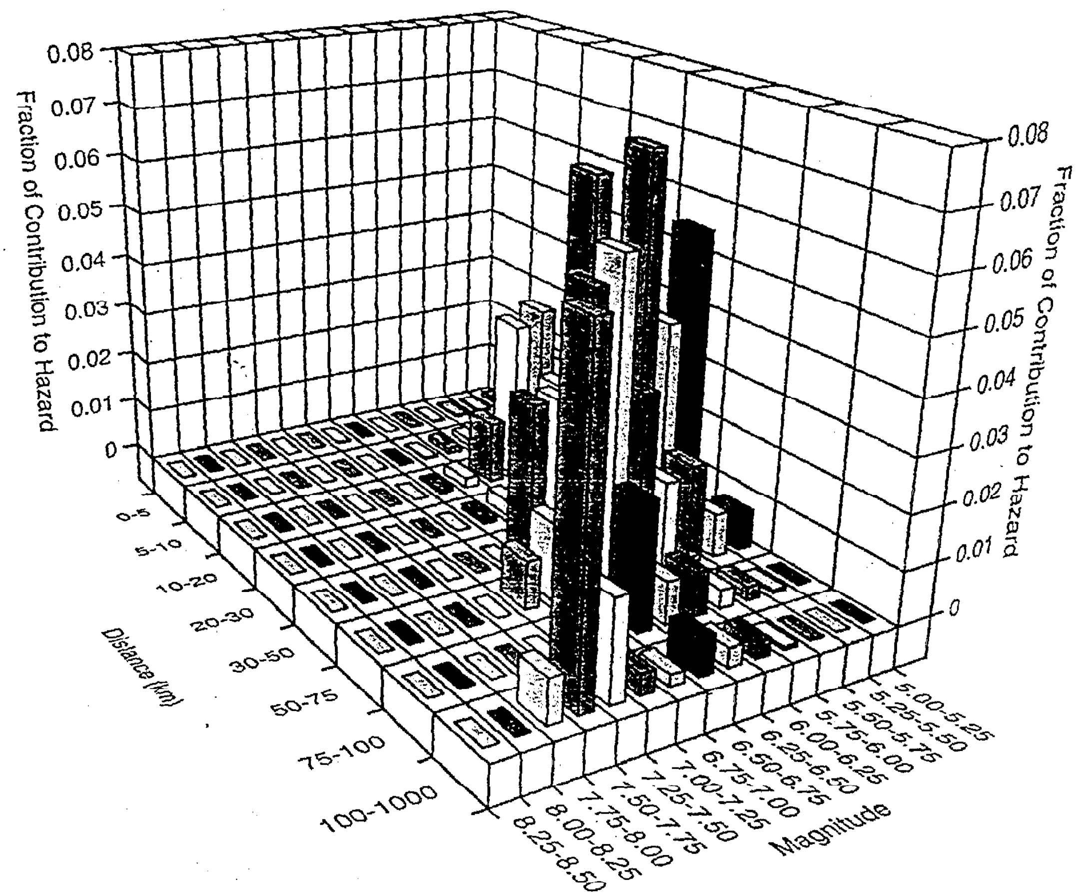

Figure A-7. Deaggregation of the seismic hazard (100 year return period) for the Terminous site based on the Lettis seismic source model for the Delta region.

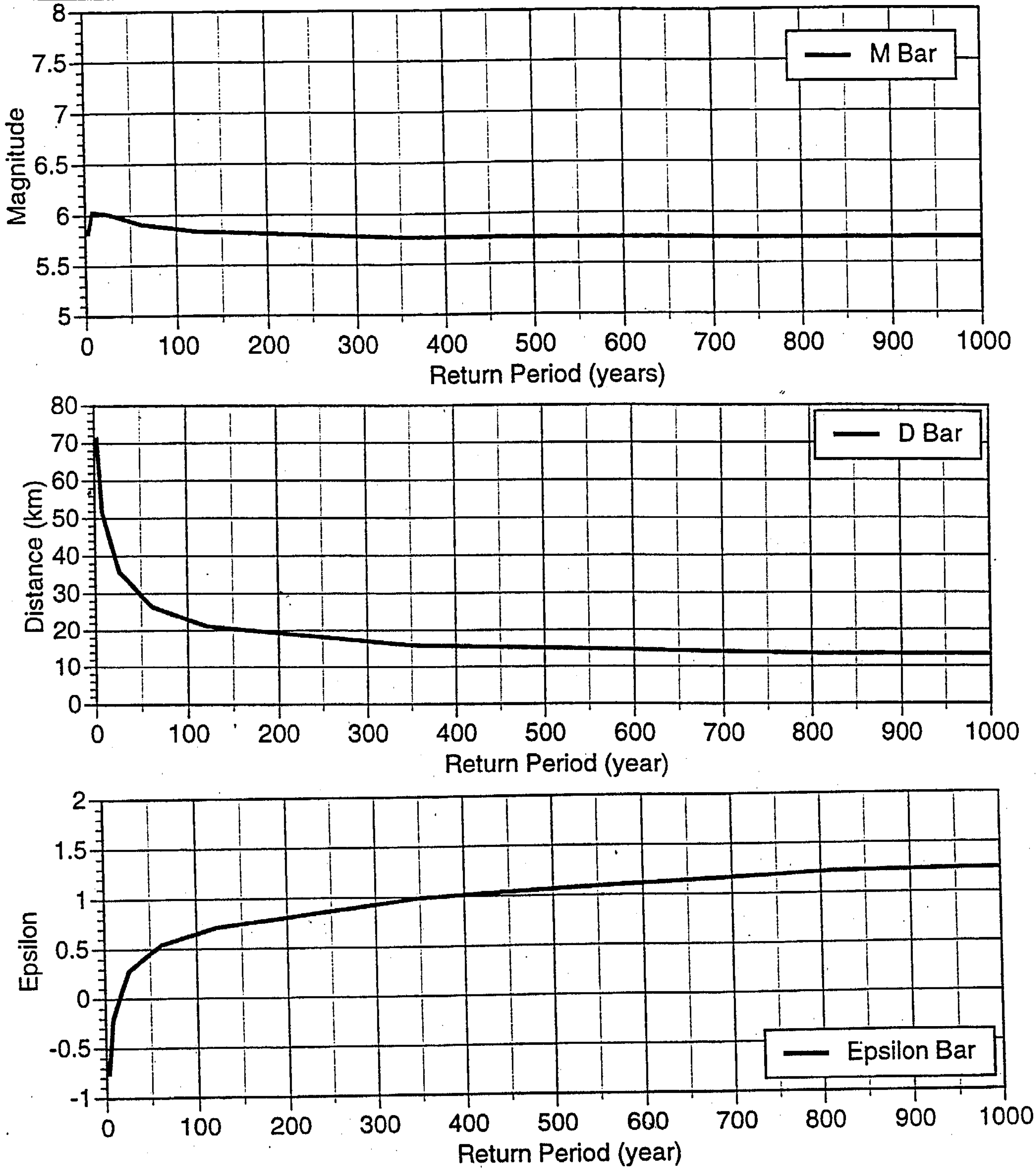

Figure A-8. Magnitude, distance and epsilon bar for the Sherman Island site based on the Lettis seismic source model for the Delta region.

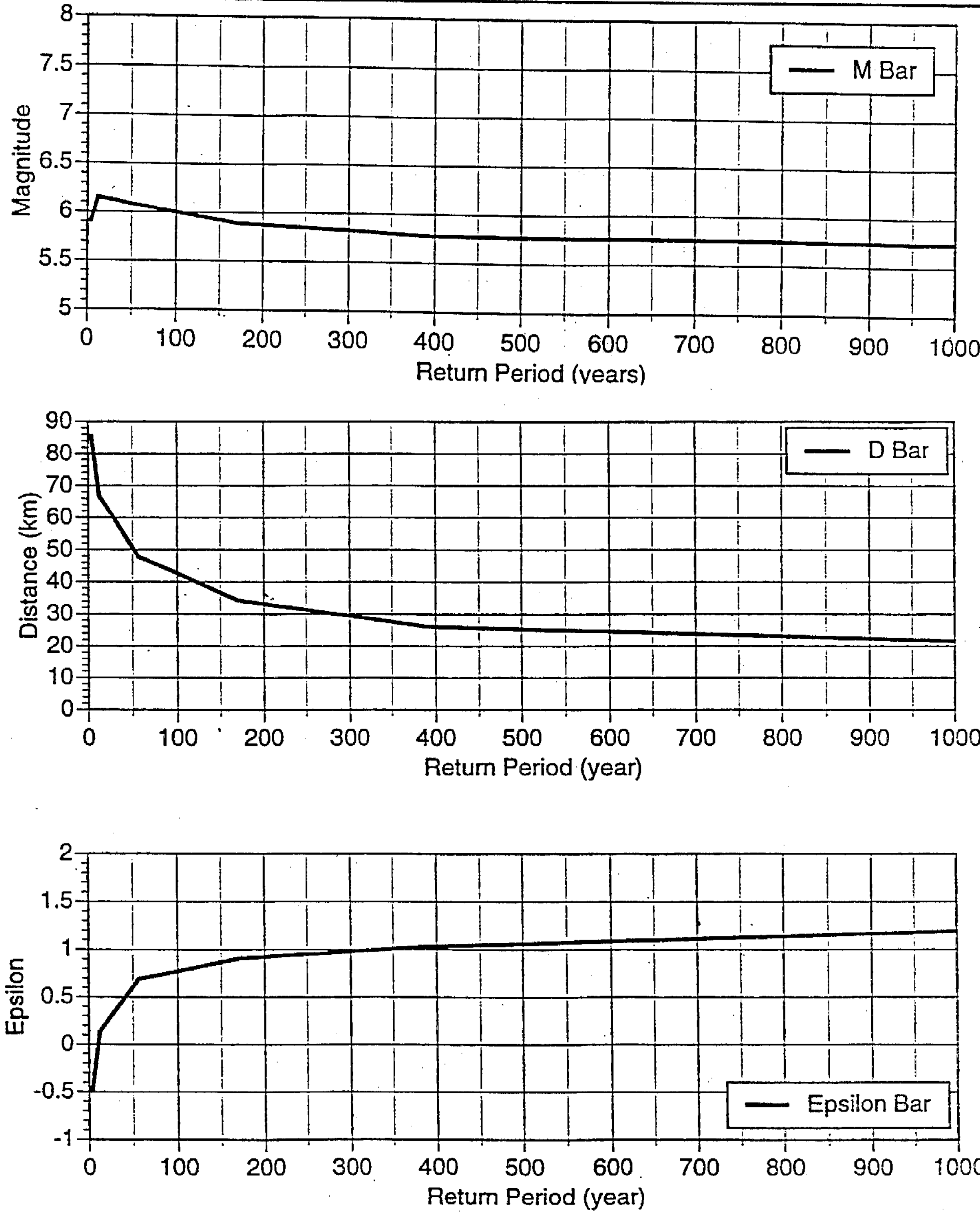

Figure A-9. Magnitude, distance and epsilon bar for the Terminous site based on the Lettis seismic source model for the Delta region.

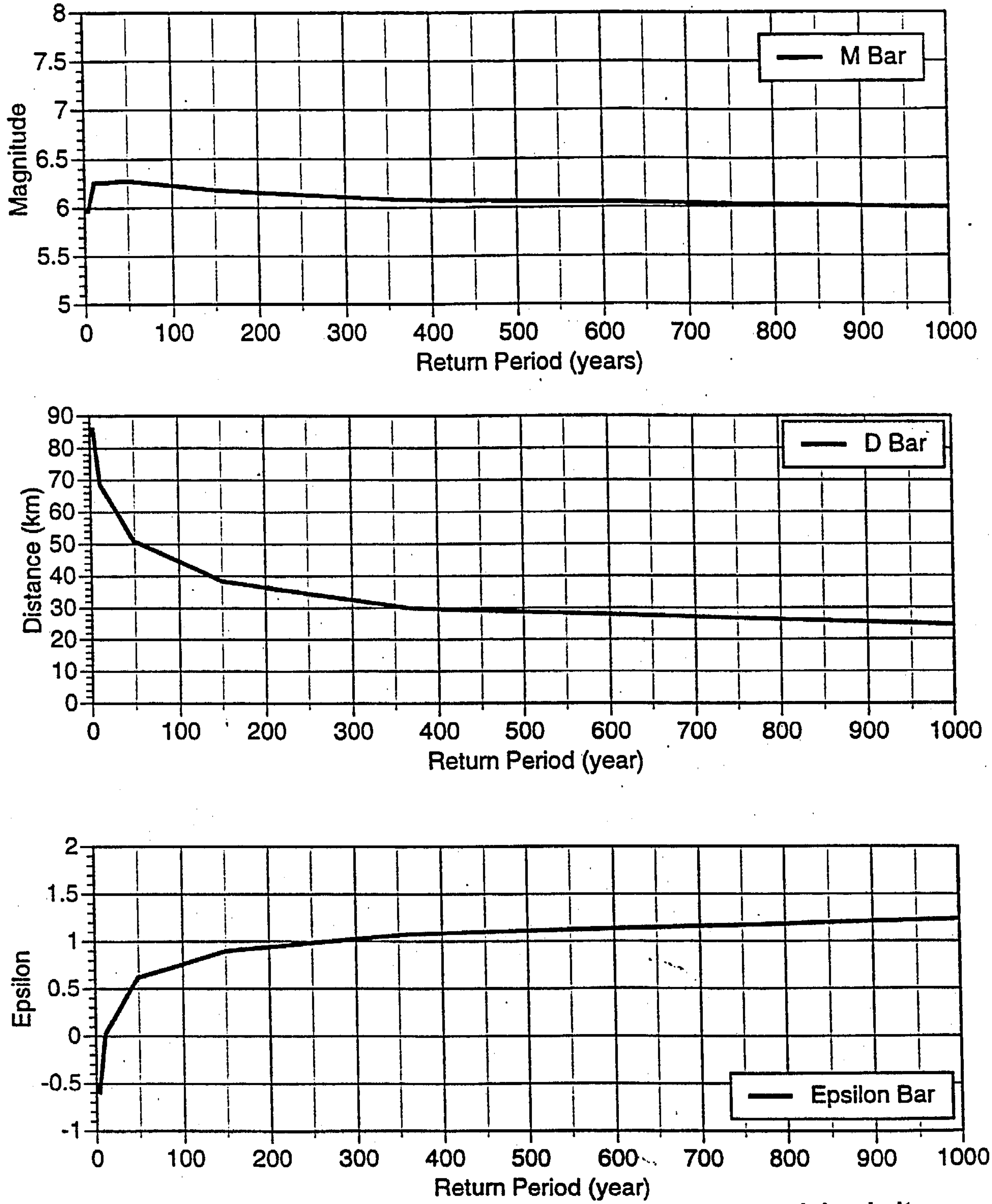

Figure A-10. Magnitude, distance and epsilon bar for the Sherman Island site based on the CRCV seismic source model for the Delta region.

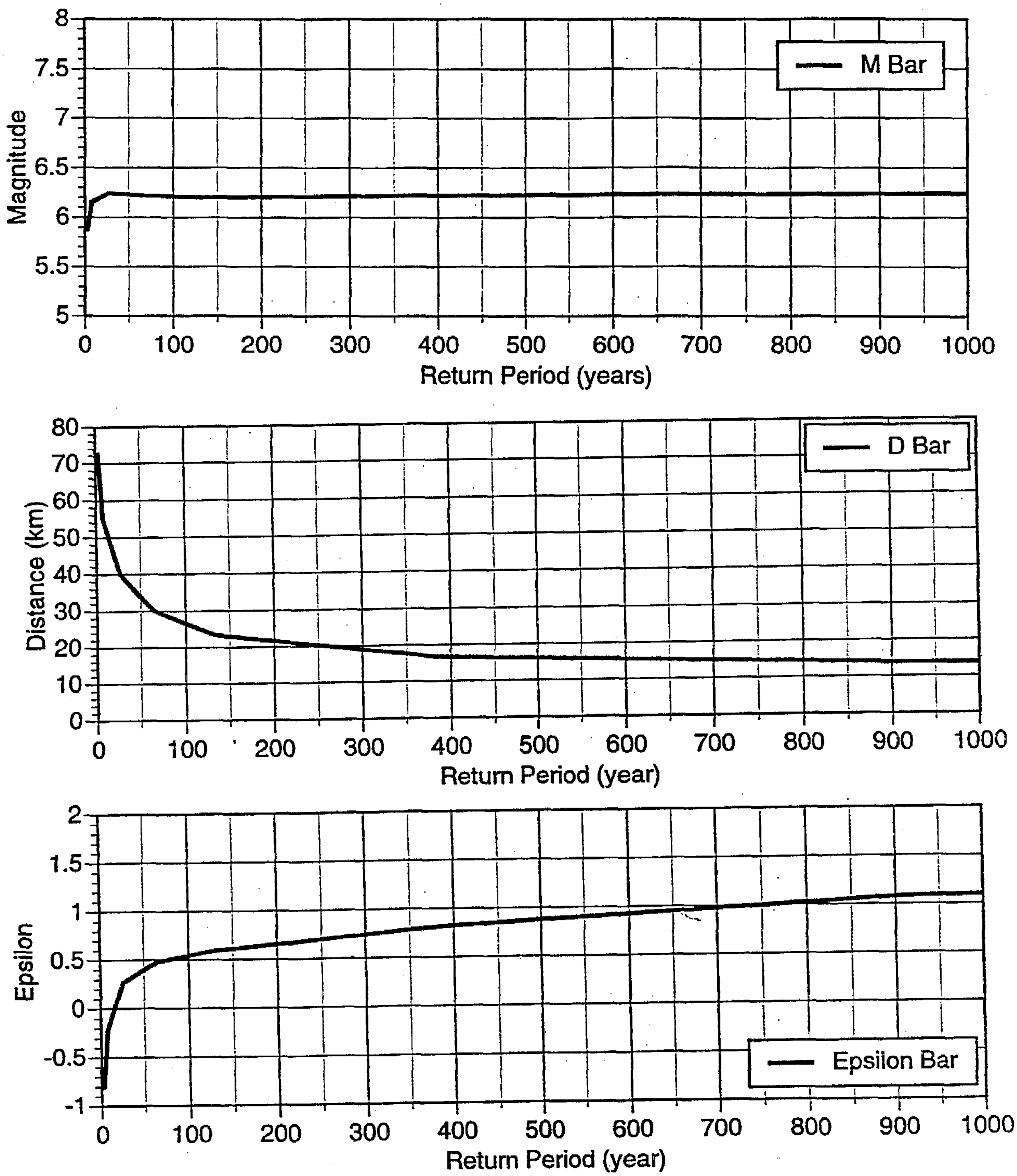

Figure A-11. Magnitude, distance and epsilon bar for the Terminous site based on the CRCV seismic source model for the Delta region.

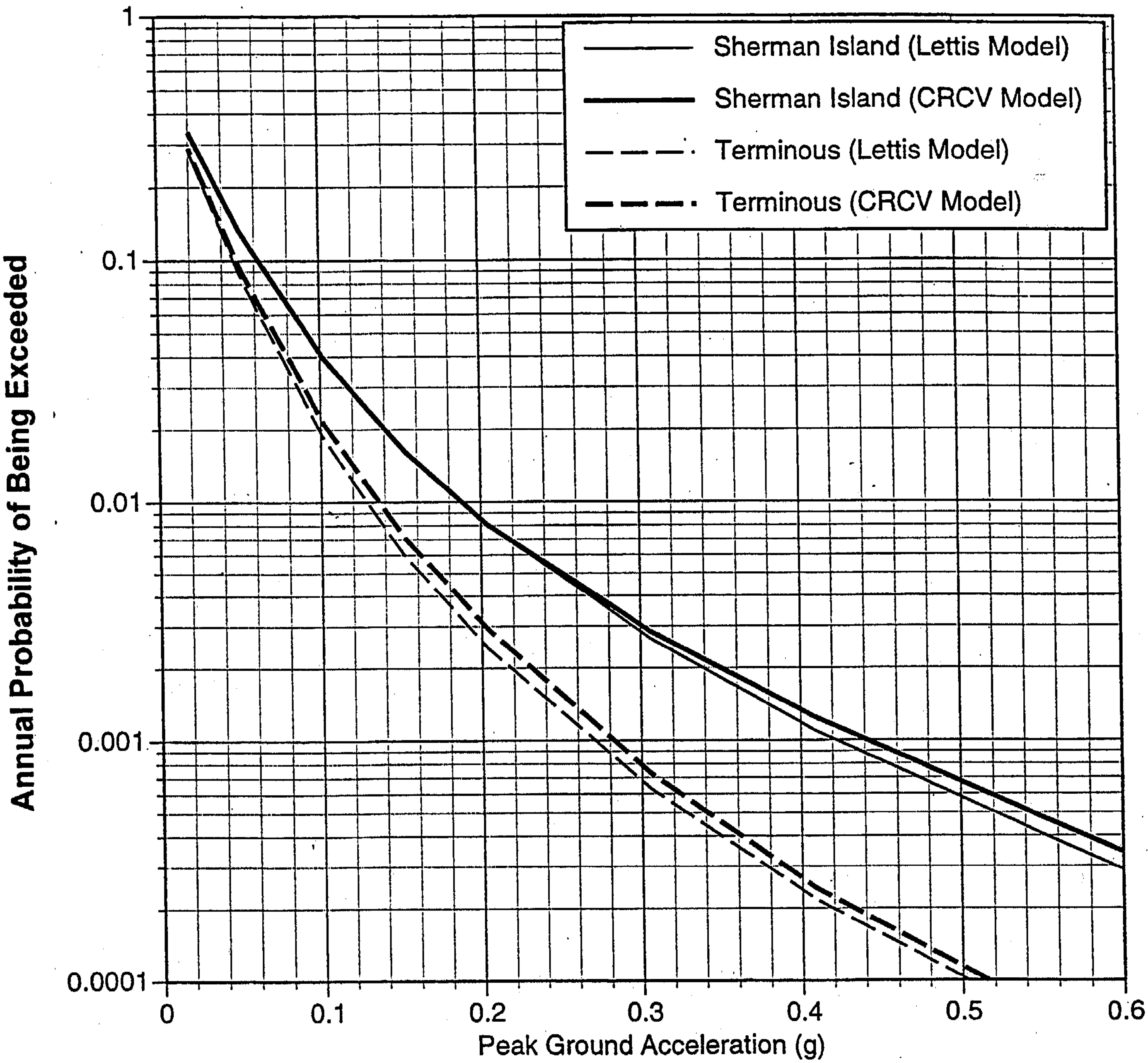

Figure A-12. Comparison of the seismic hazard for the Sherman Island and Terminous sited based on both the Lettis and CRCV seismic source model for the Delta region.

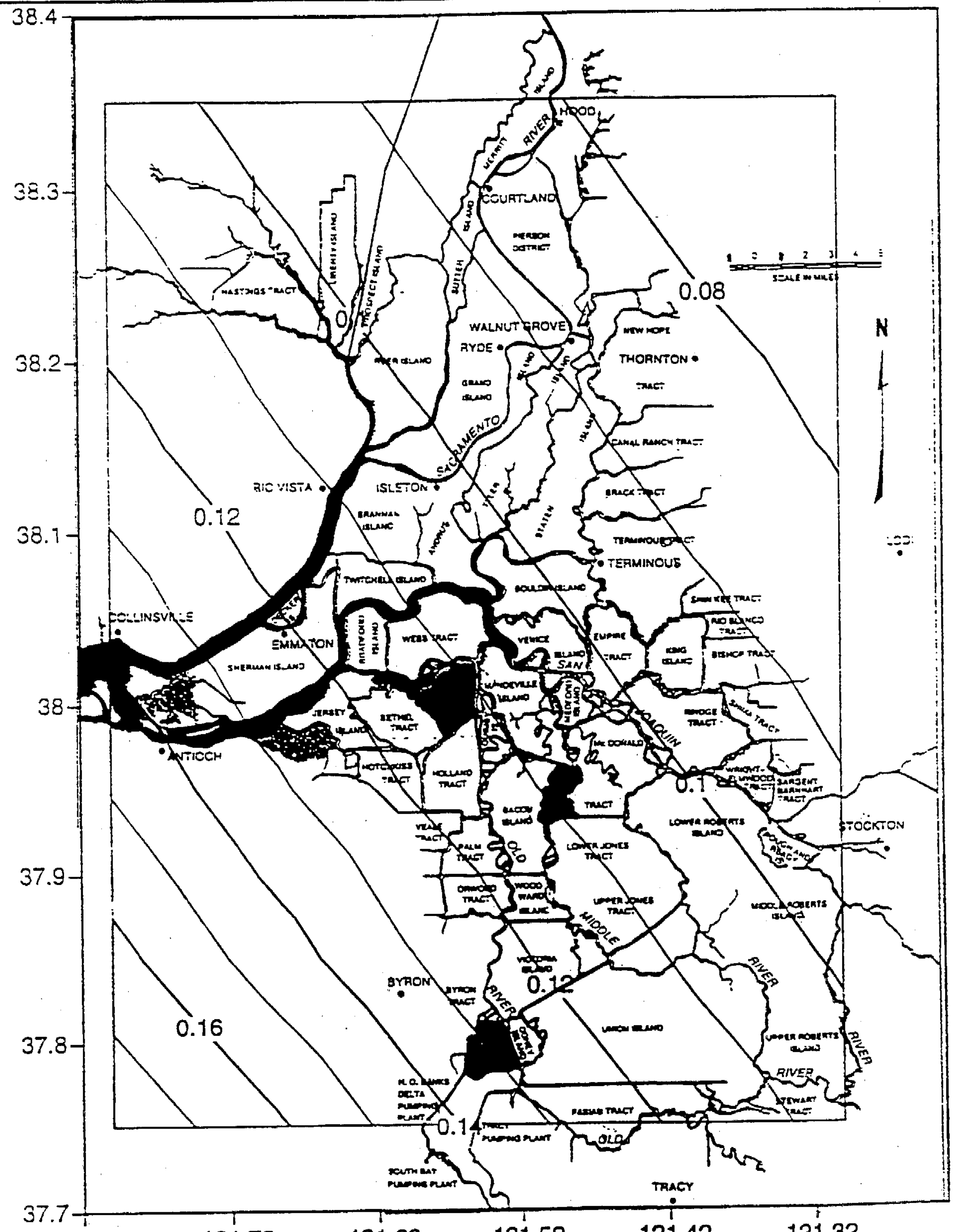

Figure A-13. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 43 years.

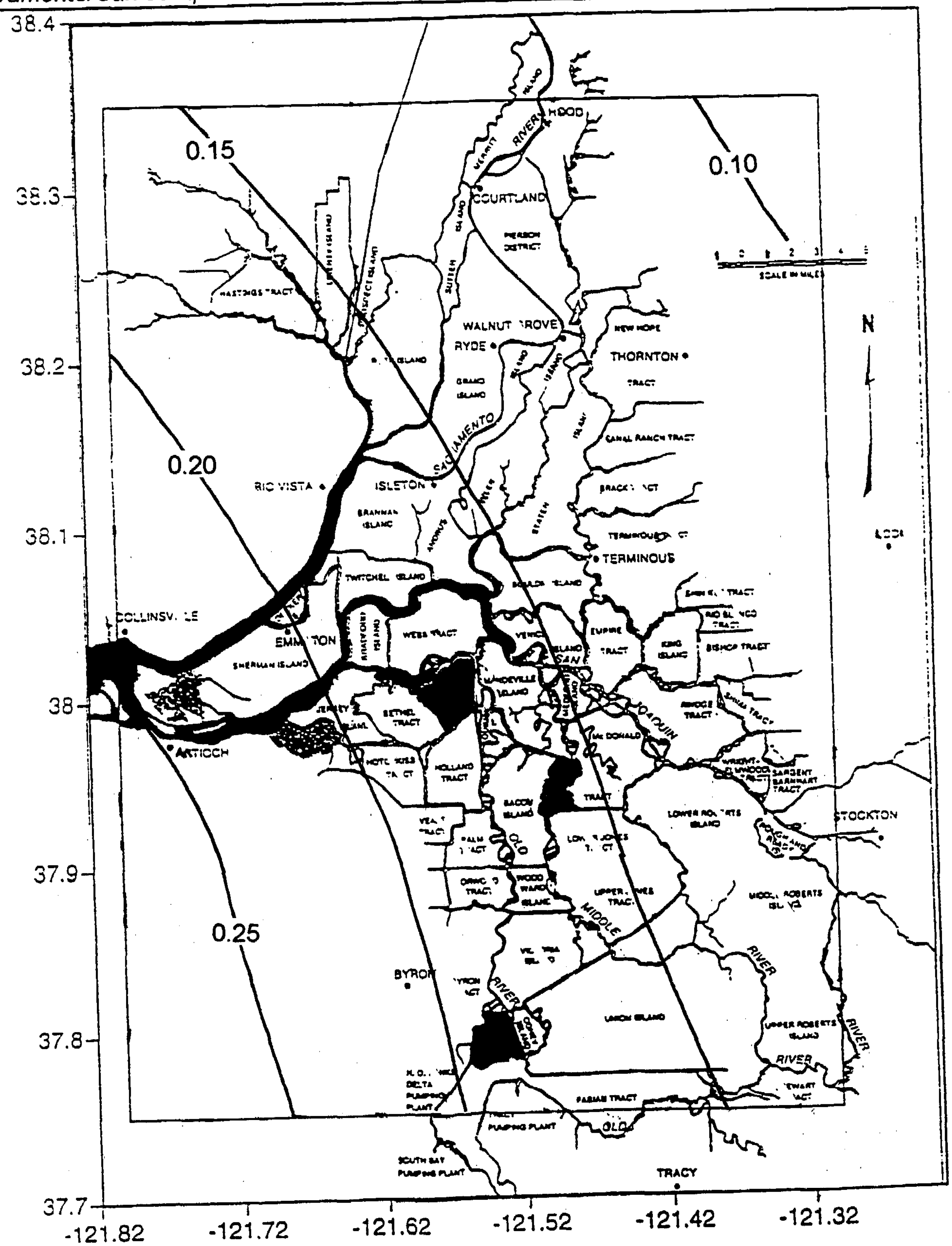

Figure A-14. **Contour map of seismic hazard (PGA) for soil site conditions for a return period of 100 years.**

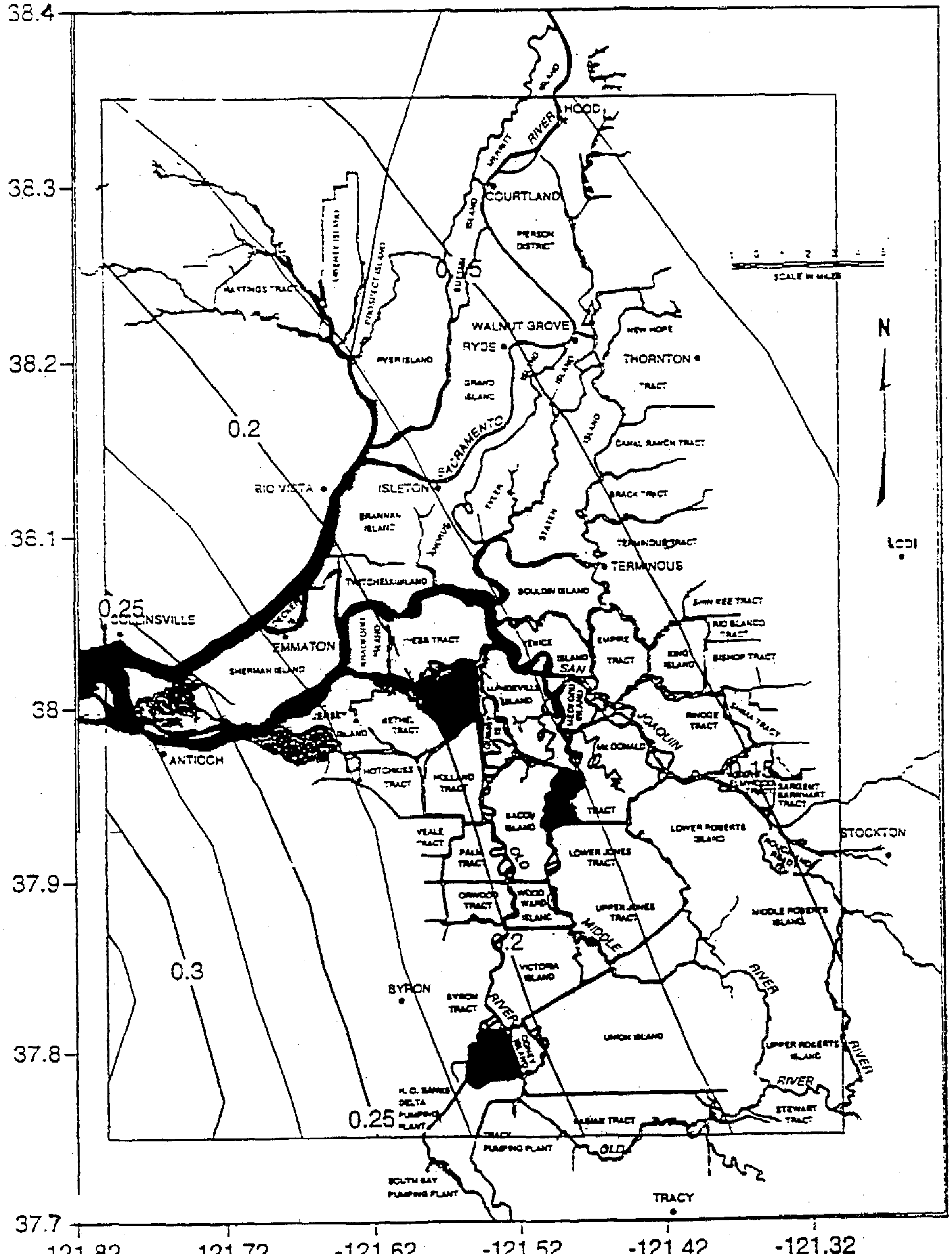

Figure A-15. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 200 years

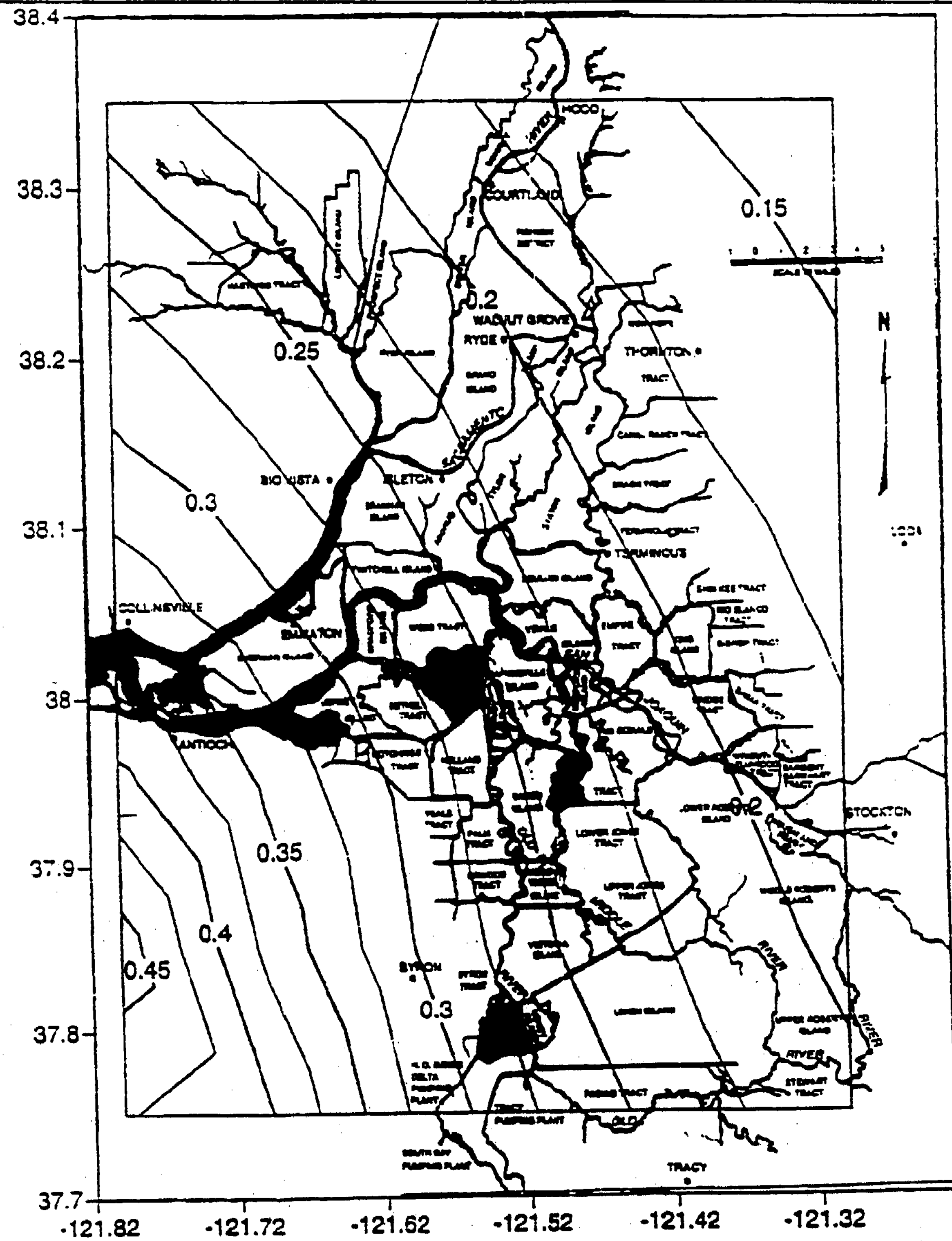

Figure A-16. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 475 years.